ECEN 5833: Low Power Embedded Design Techniques

CUBIT

Smart Measuring Instrument

Team Name: Cubit

Team Members: Rajat Chaple

Saloni Shah

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1.1 Background

A measuring tape is used in a myriad of commercial businesses like construction, tailoring, warehouses as well as in day-to-day life. The first standard measuring tape was invented in 1850s and till now we have been using the same product. Although, since 18^{th} century the world has advanced in every possible way, we still use the same measurement technique. The conventional measuring tape has ample of drawbacks like taking and maintaining measurements is very tedious, also all the measurements taken are majorly single use. It is high time that we modernize our method of taking measurements and digitize the data which can be easily stored and accessed from anywhere.

1.2 Project Summary

For the course project, our team is designing a smart measuring instrument which will have the capability to take precise linear and angular measurements and transmit the data over to a mobile application using Bluetooth. Primarily, this device will have an encoder-wheel assembly which can be used to take measurements over a straight or curved surface very accurately. A high precision rotary encoder will be helpful in giving high resolution results. Moreover, we will also install an inertial measurement unit (IMU) sensor to take different angular and device orientation data. Both measurements can then be transmitted to a mobile app connected to the product using Bluetooth. This data will also be displayed on an LCD. This device will run on a small battery, and it will also contain an energy harvesting system using solar panel to recharge the battery. All these components will be interfaced with a single Blue Gecko board. The device will operate in low power mode by implementing load power management and utilizing minimum current for required peripherals.

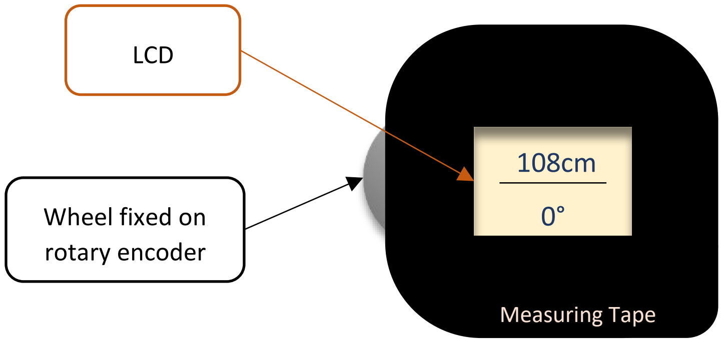

Figure 1: Product Concept

1.3 Product Application

- This product can be used to fulfill majority of measurement requirements like taking size data of a straight or uneven surface and taking angle measurements.
- This product can be used in small industries, construction sites, fashion companies and regular households.
- This product will eliminate the need to manually store measured data.
- This product will be low cost, low power consuming with energy harvesting mechanism.
- This product will use long lasting rechargeable batteries unlike single usage dry cells.

1.4 Block Diagram

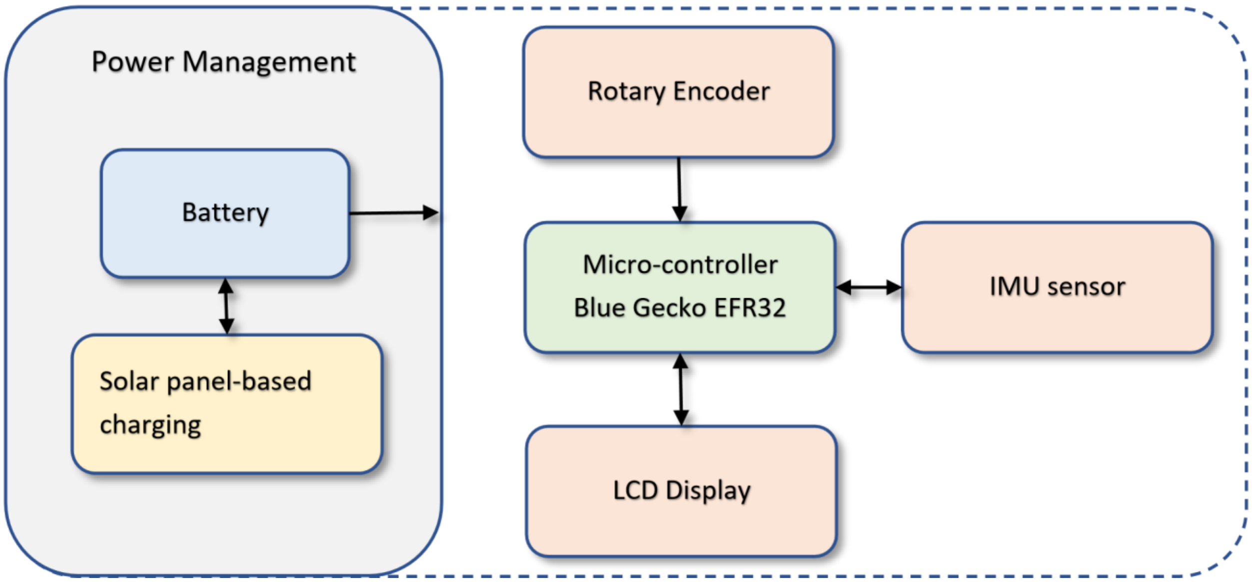

Figure 2: Block Diagram

1.5 Product Components

Table 1: Components List

Component		Part No.	Load Power Management
Microcontroller	Silicon Labs Blue Gecko		
Radio	EFR32BG13		✓
Battery	Lithium Ion/Lithium Polymer	[LP802036JU+PCM+2 WIRES 50MM Jauch Quartz | Battery Products | DigiKey]	
PMIC	BQ25570	[BQ25570RGRT Texas Instruments | Integrated Circuits (ICs) | DigiKey]	

Buck Converter	TPS62842 Or PMIC internal buck converter	TPS62842DGRR Texas Instruments | Integrated Circuits (ICs) | DigiKey	
Sensor	IMU sensor	BNO005 (To be acquired from Professor)	✓
	Rotary Encoder	Magnetic Rotary Encoder Magnetic Wheel Assembly	✓
	Ultrasonic Sensor	Adafruit Ultrasonic Sensor	✓
HMI	LCD Display	Adafruit SHARP Memory Display Breakout - 1.3" (Acquired from Professor)	✓
	Push Buttons	Available	
Energy Harvesting System	Solar cells	Monocrystalline solar cells	

1.6 Proposed Product Demo

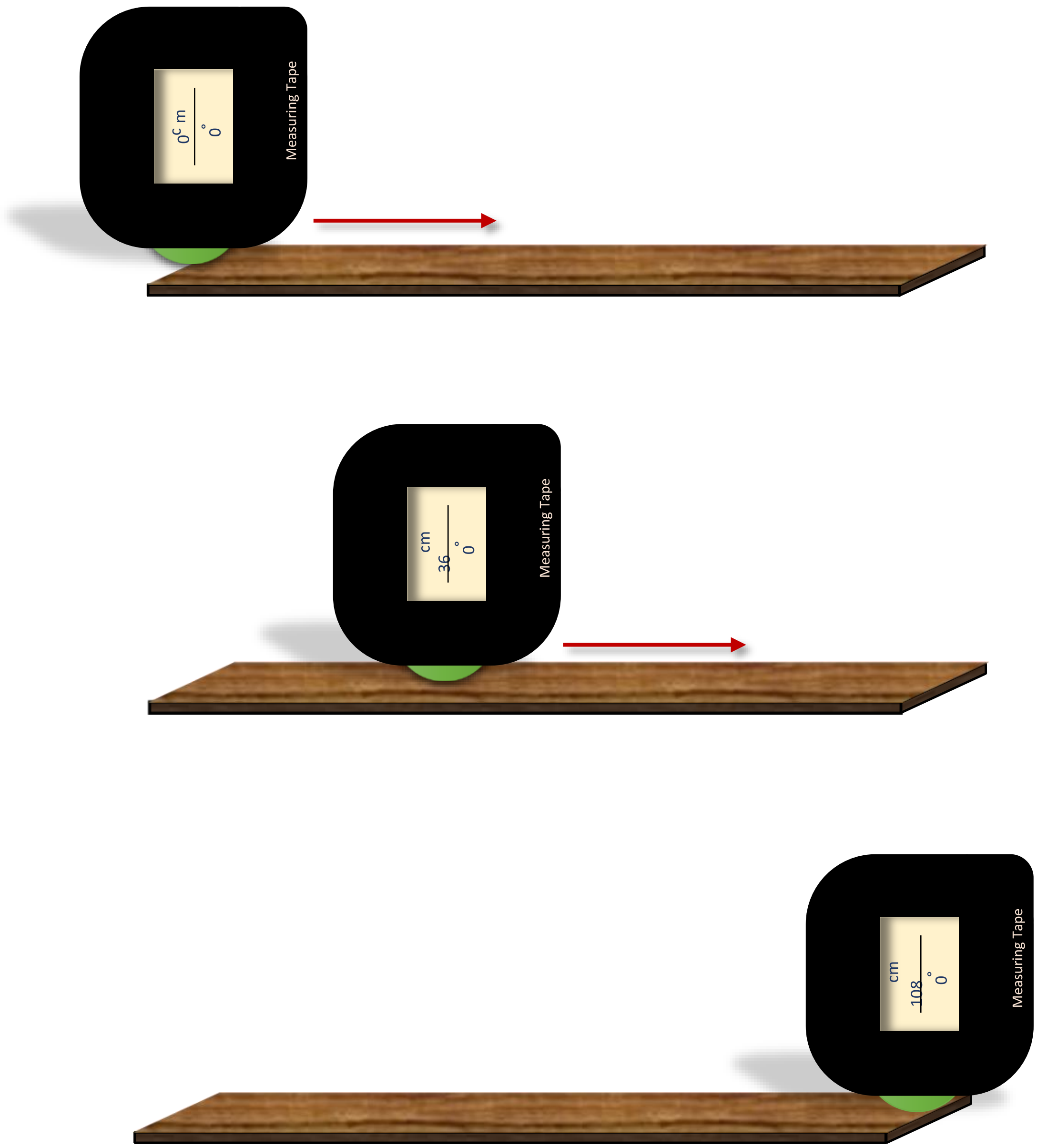

Figure 3: Proposed Product Demo 1

As shown in the above image, this measuring tape can be used to measure any surface. The wheel encoder assembly installed on the product can be slid over a flat or uneven surface to get size value accurately. This measuring tape will have a high resolution in centimeter because of the use of a precision Rotary encoder with large number of pulse detection in a single rotation.

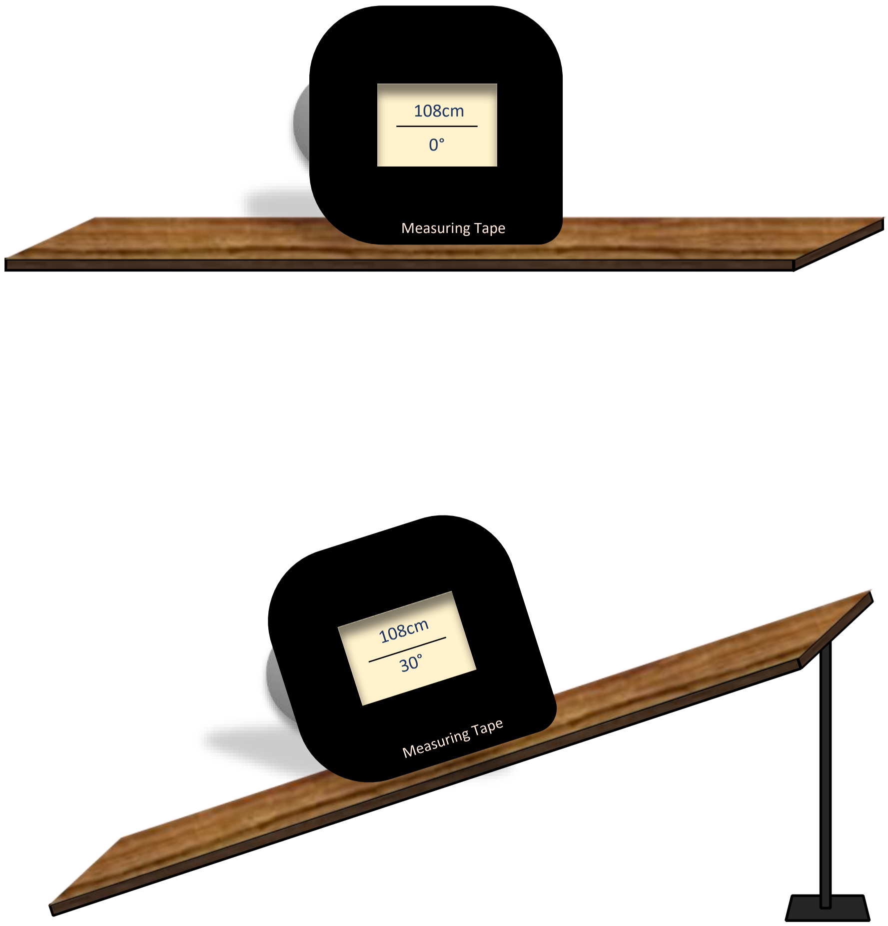

Figure 4: Proposed Product Demo 2

The above image shows how an angle measurement can be carried out using the product. This angle can be measured in any orientation of the device. The angle measurement will also be highly accurate due to the IMU sensor.

1.7 Product Features

- Free android app to store and manage measurement data
- Bluetooth connectivity of mobile phone with the device
- Rotary encoder-wheel assembly for linear measurement
- IMU sensor for accurate angle measurement
- LCD Display for better user experience
- Energy harvesting mechanism using solar panels
- Load power management by turning on only required peripherals
- Single rechargeable LiPo battery which can power the complete device

1.8 Product Specifications

- Dimensions: 100mm x 70mm
- Weight: 100g
- Wireless range: 100 m
- Size accuracy: ± 1 cm
- Angle accuracy: ± 1°
- Product Warranty: 2 years
- Operating Temperature: 0°C - 65°C
- Internal sensors and peripheral operating temperature:

Table 2: Temperature specifications for sensors

Sensor	Operating Temperature Constraints
Blue Gecko	-40 to 85 °C
IMU	-40 to 85 °C
Rotary encoder	-40 to 150 °C
LCD Display	-40 to 70 °C

Project Update 2

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Saloni Shah

Date: 01/29/2022

2.1 Activities accomplished in past week

- Studied mouse scroll-wheel encoder assemblies to decide the decide the mechanical assembly for final product. Disassembled 4 different optical mouses to explore different assemblies.

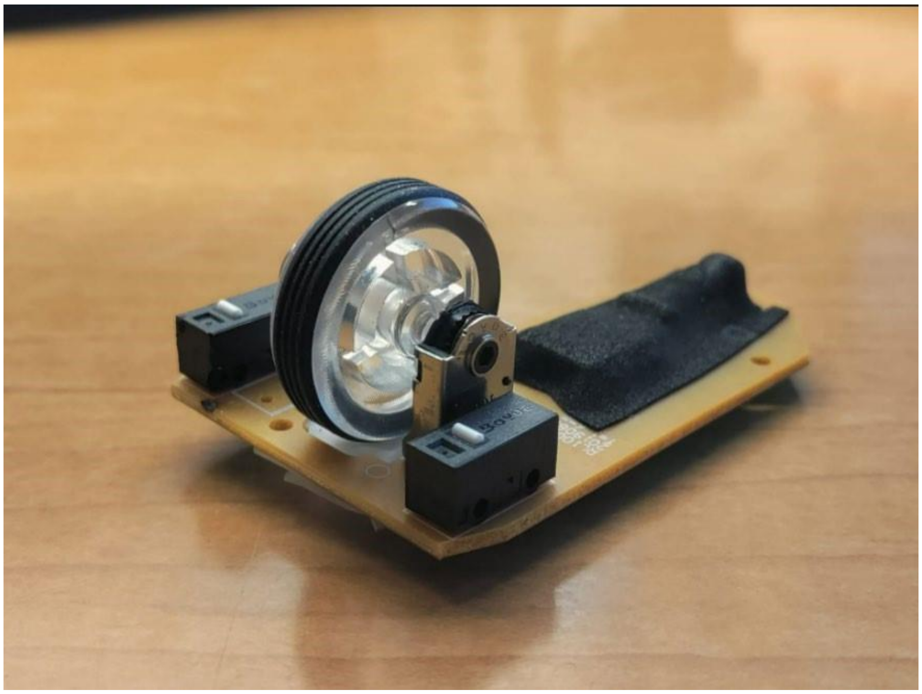

Figure 5: Scroll wheel encoder assembly

- Measured PPR(Pulse per rotation) of rotary encoder and circumference of wheel to estimate linear measurement resolution. ○ Finalized ultra-low power Graphic LCD display. ○ Estimated total power and energy consumption of the product.
- Worked on project planning and estimated timeline.

2.2 Activities for the coming week

- Finalize battery and solar panel based on energy consumption requirements. ○ Finalize Power management IC.
- Work on power supply circuit for the product.

2.3 Energy model for the product:

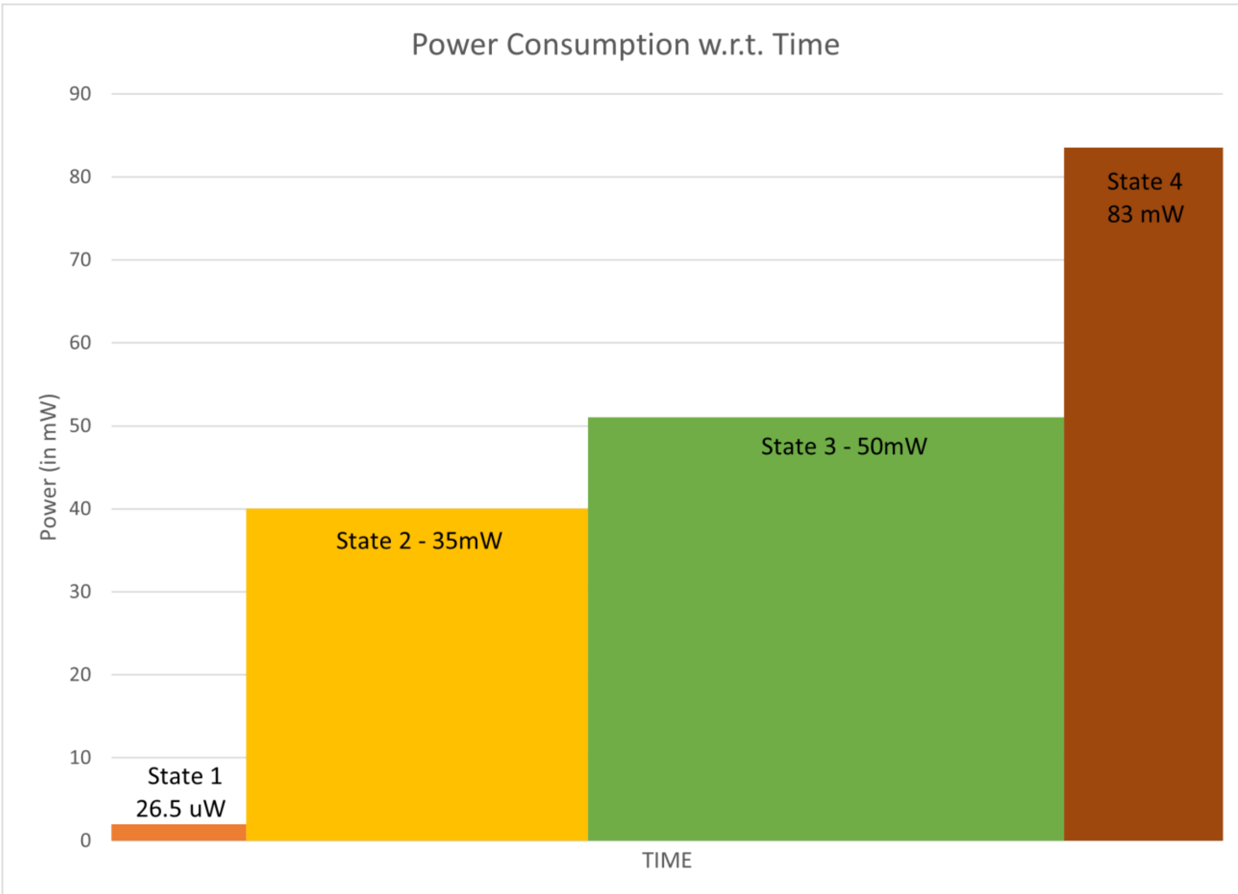

Figure 6: Energy model

2.4 Sensor selection:

2.4.1 IMU Sensor: BNO005

- This sensor works on I2C as well as UART.
- We will be interfacing the sensor using I2C as data transfer over UART communication takes longer and even though it consumes less energy, overall efficiency of UART decreases. Moreover, for transfer of larger data bytes I2C consumes the same amount of energy. (These assumptions were made using this reference.)
- This sensor will require external load switch as after start-up it only enters low power mode and suspend mode. (Even in suspend mode it consumes 40uA of current).

2.4.2 Rotary encoder

- This mechanical encoder has just 2 digital pins which can be wired directly as input to the controller. The encoder generated pulses gives the angular position of the axis and can then be converted to digital output.
- The encoder will also require external load switch as it does not have internal circuitry to turn power off.

Online Project Management using Monday.com

2.5 Program Flowchart:

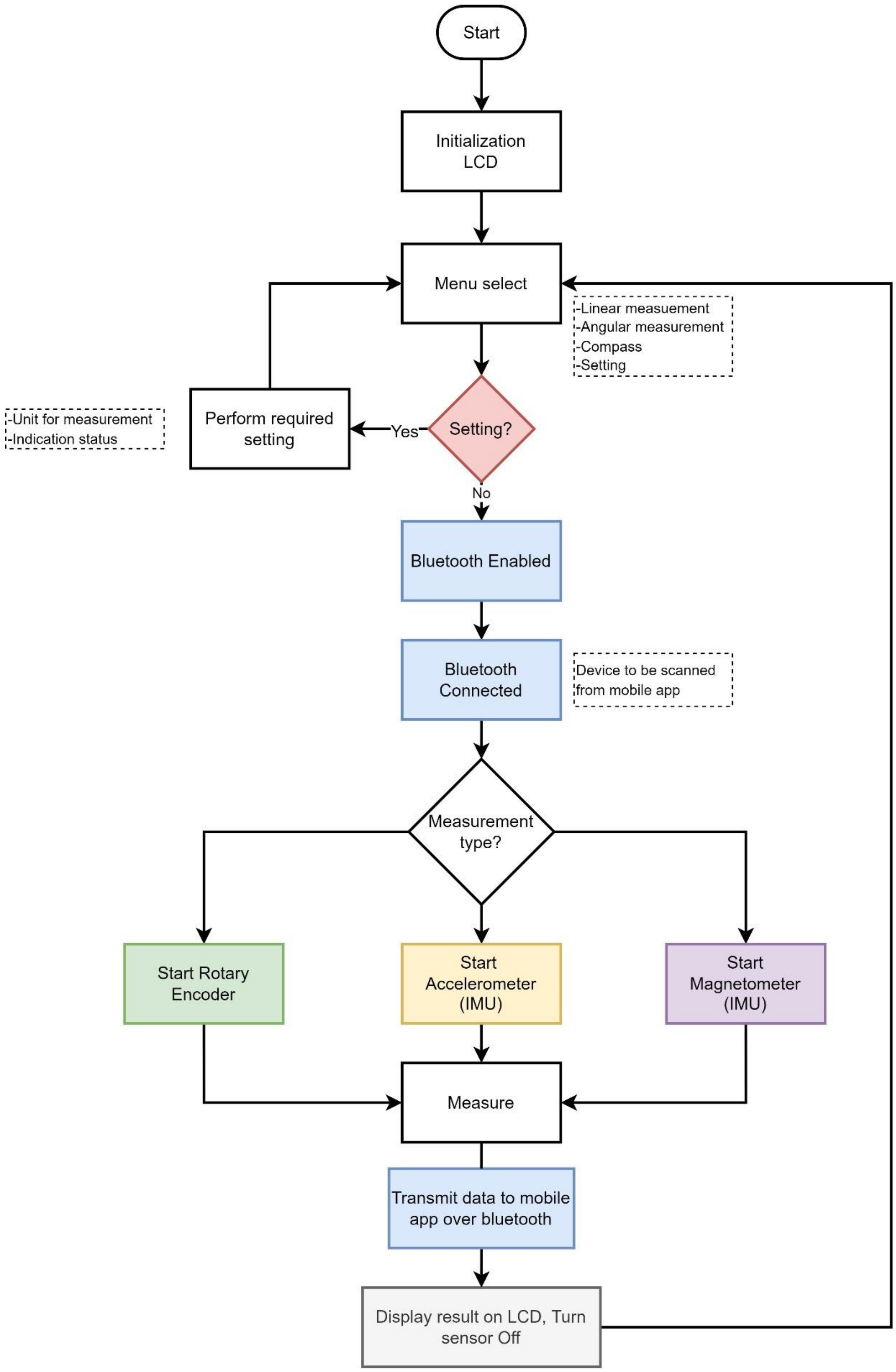

Figure 7: Flowchart

Project Update 3

ECEN 5833: Low Power Embedded Design Techniques

CUBIT

Smart Measuring Instrument

Team Name: Cubit

Team Members: Rajat Chaple

Saloni Shah

Date: 02/05/2022

3.1 Activities accomplished in past week:

- Finalized energy storage element (battery) based on energy consumption requirements.
- Finalized Power management IC and buck-converter IC.
- Practically implemented measurement system using mechanical rotary encoder, string-pulley assembly and interfaced it with Arduino. Found out that the rotary encoders have a limitation on how fast it can detect rotations i.e. it can only detect signals correctly at less than 160 rpm.

Figure 8: Assembled rotary encoder with a string-pulley

Figure 9: Measuring the length of a ruler using the assembly

Arduino serial monitor output with number of pulse counts and calculated length

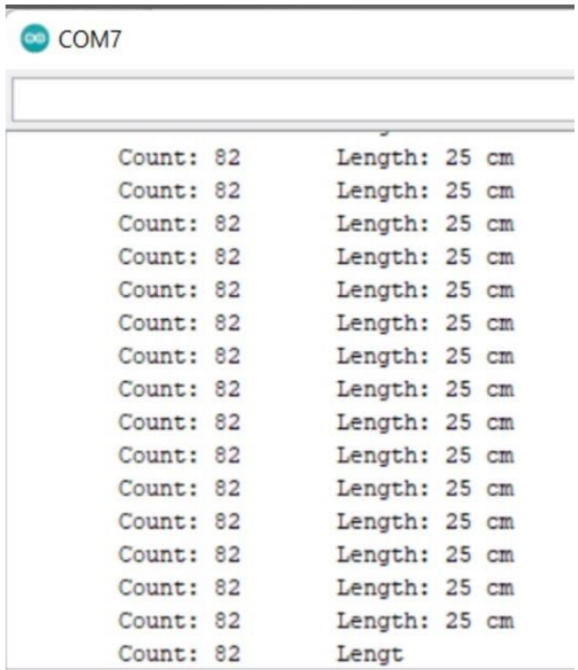

Figure 10: Optical Rotary Encoder output

- Changed the required rotary encoder from mechanical to magnetic due to speed constraints and higher chances of signal misses in the mechanical encoder.
- Finalized required magnetic rotary encoder and ultrasonic sensor for measurement applications.

3.2 Activities for the coming week

- Finalized energy harvesting element (solar panel) based on energy consumption requirements.
- Design product power supply circuit.
- Interface LCD display with Blue Gecko Evaluation Module.
- Finalize other required components for the product schematic design.

Power Storage Element Selection
- Expected runtime using supercapacitor = 1.36 hours
- Expected runtime using battery = 3 days (8 hours per day)[1]

3.2.1 Super Cap vs Battery

Required peak current: 25 mA

Average current consumption: 13.68 mA

Average Charge requirement for continuous 8 hours operation: 110mAh

Average Energy Required for 8 hours of operation: 328.4 uWh

Ambient Temperature Conditions: Room Temperature (about 25° C)

Table 3: Super cap - Battery comparison

Super Cap	Battery
Steep discharge curve	Higher operating time
Large leakage current (30 uA)	Very less leakage current (2%/year)
Cannot handle required peak current	Can handle upto 1A peak current
Lower energy density	Higher energy density
Can operate in very low temperature	Dispenses less energy in low temperatures
Lower ESR power loss	Higher ESR power loss

Table 4: Supercap and battery specifications

Design Requirements	Super Cap (Tecate 100F)	Battery (Jauch 480mAh)
Useable Energy	234.5J[2] - 18.6mAh	480 mAh
Peak Discharge Current		1A
Recharge time		2 hours @ 0.5C
2 years of use, 300 charges	500,000 cycles	300 cycles ~ 80% capacity usage
Leakage current or rate	3 uA	Less than 2-3%
ESR	210 mΩ	
Mechanical Dimensions	12.5 x 25 mm	38 x 20.5 mm

[1] Refer attached spreadsheet for calculations

[2] Refer attached spreadsheet

3.3 Power Management Unit Selection

3.3.1 Determining the required voltage range for the product

- To decide the operating voltage range for the product, we looked at the input voltage range of the peripherals utilized in the system. The below table shows the minimum and maximum input voltage range of the sensors and MCU.

Table 5: Voltage range for components[1]

Sensor	Vin(min)	Vin(max)	Current Consumption
Blue Gecko	1.8V	3.8V	4uA
IMU	2.4V	3.6V	12.3mA
Rotary encoder	3V	3.6V	15mA
LCD Display	3V	5V	4uA

- Based on the above calculations, we decided to operate all the peripherals at 3.0V as to utilize maximum possible battery capacity and increase the operating time of the system.
- The approximate range of the supply voltage will be from 3.0-3.6V.

[1] IMU datasheet: BNO055 Datasheet (mouser.com)
Blue Gecko datasheet: EFR32BG13 Data Sheet: Blue Gecko Bluetooth® Low Energy SoC Family (silabs.com)
Magnetic Rotary Encoder datasheet: AS5147P-TS_EK_AB ams | Development Boards, Kits, Programmers | DigiKey LCD Display datasheet: Data+sheet.pdf (adafruit.com)

3.3.2 Determining the power management topology

- Considering that the power source battery gives maximum 3.7V and our required voltage supply for the peripherals is about 3.0V, which is always lower than supply voltage we decided to implement a buck converter to meet our power requirements.
- The primary reason for choosing a buck converter as opposed to a buck-boost is that most Lithium-Poly batteries have a plateau from 3.5-3.6V and very little charge below this plateau, limiting the usefulness of the buck-boost converter and its wide input voltage range2.
- Moreover, the buck-boost converter also has one additional MOSFET as compared to the buck converter which increases power loss and decreases efficiency of the converter.
- Keeping this in mind, we searched for a buck converter IC, with high efficiency, low quiescent current, low cost, and smaller footprint.
- All these requirements were successfully met by the buck converter TPS62840[3].

3.3.3 Determining Regulated or Unregulated Power Source

- While deciding whether to use regulated or unregulated power source, we carried out following calculations to understand efficiency of both topologies.

Assumed product usage of 60 minutes or 3600 seconds

Assumed number of measurements in 1 hour, average of 20 measurements

Assumed period for one measurement, average of 13 seconds

On duty cycle = (20 measurements * 13 seconds) / 3600 = 7.2% Off

duty cycle = 92.8%

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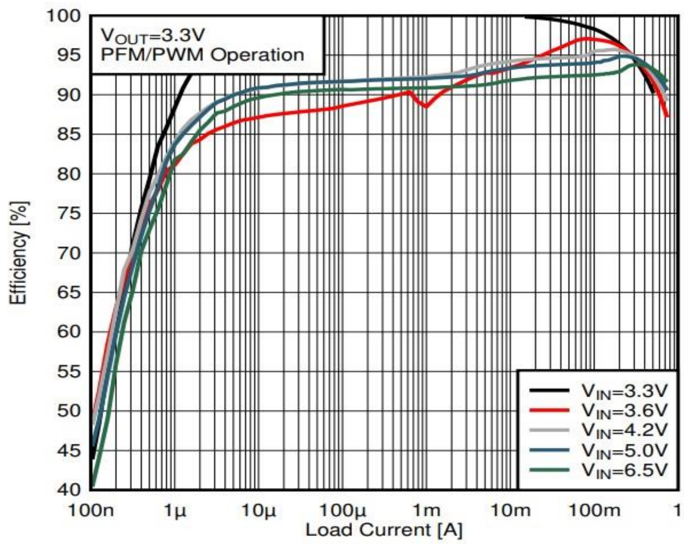
[2] EETimes - Buck-boost vs. buck converter: it's about battery life in portables

[3] TPS62840 datasheet: TPS62840 1.8-V to 6.5-V, 750-mA, 60-nA IQ Step-Down Converter datasheet (Rev. D) (ti.com)

TPS62840 Buck converter Efficiency Curve

- Off duty cycle = 0.015-0.020 mA
  Estimated 87.5% efficiency
- On duty cycle = 15-20 mA range
  Estimated 94% efficiency



R_{SET} = 267 kΩ to GND

Figure 19. Efficiency Power Save Mode
V_{OUT} = 3.3 V

For regulated power case (using TPS62840 buck converter):

- On duty cycle
  - TPS62840 efficiency ~3.6V input and 15,500uA is 94% + 0.06uA Iccq
  - Weighted avg power OOB = (On duty cycle * (15500 + 0.06) * 3.0V) / 94%
  - Weighted average power out of battery = 3561 uW o Off duty cycle

- TPS62840 efficiency ~3.6V input and 20uA is 87.5% + 0.06uA Iccq
- Weighted avg power OOB = (Off duty cycle * (20 + 0.06) * 3.0V) / 87.5%
- Weighted average power out of battery = 63.8 uW ○ Total Average Power out
- Weighted on duty cycle average power + Weighted off duty cycle average power = 3561uW + 63.8uW = 3624.825 uW

<u>For unregulated power case (using Blue Gecko internal LDO):</u>

○ On duty cycle
- Gecko efficiency ~3.6V input and 15,500uA is 83.33%
- Weighted average power OOB = (On duty cycle * 15500 * 3.0V) / 83.33%
- Weighted average power out of battery = 4017.7 uW ○ Off duty cycle
- Gecko efficiency ~3.6V input and 20uA is 83.33%
- Weighted average power OOB = (Off duty cycle * 20 * 3.0V) / 83.33%
- Weighted average power out of battery = 66.81 uW ○ Total Average Power out
- Weighted on duty cycle average power + Weighted off duty cycle average power = 4017.7uW + 66.81uW = 4084.5 uW

Increase in battery life using regulated power = 1 - $\frac{3624.825}{4084.5}$

= 11.25%

Based on above calculations, we decided to use a regulated power source since it provides longer battery life. Moreover, we have a higher on duty cycle, higher power on to power off ratio, higher efficiency at light load and low quiescent current which justifies the use of regulated power source.

4.4. Determining the Power Management IC ○ The primary criteria for selecting a PMIC were low minimum input voltage limit to support very low voltage from energy harvesting element (solar cell) and efficient boost converter. A simple and efficient circuitry for energy harvester is required which were available in PMIC BQ25570.

- The input voltage supported in this IC is 0.1-5.1V. Also, many typical solar cells have an output voltage of 0.1V.
- Another important criterion is to have a wide range of input voltage from battery to support lower battery power which is 2-5.5V in case of BQ25570.
- This IC also has higher charging current capacity (maximum 285mA) for fast charging from external charger or a USB charging port.
- BQ25570 also has internal Programmable Maximum Power Point Tracking (MPPT) circuitry for optimal energy extraction from energy harvester like solar panel.
- Moreover, BQ25570 has internal boost as well as buck converter to boost low input voltage from the energy harvester and simultaneously regulate the output voltage[4].

[4] BQ25570 internal buck converter vs external TPS62840 buck converter: The TPS62840 buck converter has higher efficiency at low current consumption than the internal buck converter.

Project Update 4

ECEN 5833: Low Power Embedded Design Techniques

CUBIT

Smart Measuring Instrument

Team Name: Cubit

Team Members: Rajat Chaple

Saloni Shah

Date: 02/12/2022

4.1 Activities accomplished in past week:

- Generated Altium components library for following parts

Table 6: Components' library list

Sr. No	Part Description	Part Number	Footprint Name	Online SnapEDA/ Octopart Link
1	Blue Gecko	EFR32BG13P732F512GM48-D	48-QFN_7x7	N/A
2	PMIC	BQ25570RGRT	21_QFN_35X35	N/A
3	IMU Sensor	BNO055	LGA28R50P4X10_380X520X100	BNO055 SnapEDA
4	Magnetic Encoder	AS5147P-HTSM	14-TSOP_5x4_4	N/A
5	Resistor	RMCF0603FT1K00	2_Chip_0603_RMCF	N/A
6	Capacitor	CL10A475KP8NNNC	CAP_0603_1MM	N/A
7	Inductor	VLS3015CX-220M-1	2_IND_3x3	N/A
8	LED (red)	150060RS75000	LED_0603_RED_WL-SMCW	N/A
9	LCD header	3502	LCD_SHARP_MEMORY_9_PIN	N/A

4.1.1 Change in the Power management strategy

- With earlier update, plan was to use PMIC bq25570 and TPS62842 buck converter. Criterion for selection of external buck converter instead of one already integrated into bq25570 was Efficiency. However, considering ON duty cycle of the product operation, efficiency would no longer be a preliminary factor under consideration.
- Also, major concern where we cannot utilize most energy from the battery was resolved using following.
  - Entire circuit would work at 3.15v
  - Buck converters have dropout voltage. This limits battery's minimum usable voltage. As per datasheet, dropout voltage is maximum output current times the buck high side resistance.

Calculations:

Maximum output current: 35 mA

Maximum buck high side resistance: 200Ω

Dropout voltage: 35 x 200 = 0.7v

- Usable battery would be in the range of 3.7v down to 3.22v.

4.1.2 Tested battery power consumption from a sample project

- As a case study one of the sample projects was arranged. Though this project's objective is entirely different than that of CUBIT, similarities in functional blocks were identified. This project also contains solar energy harvesting, PMIC and a load.

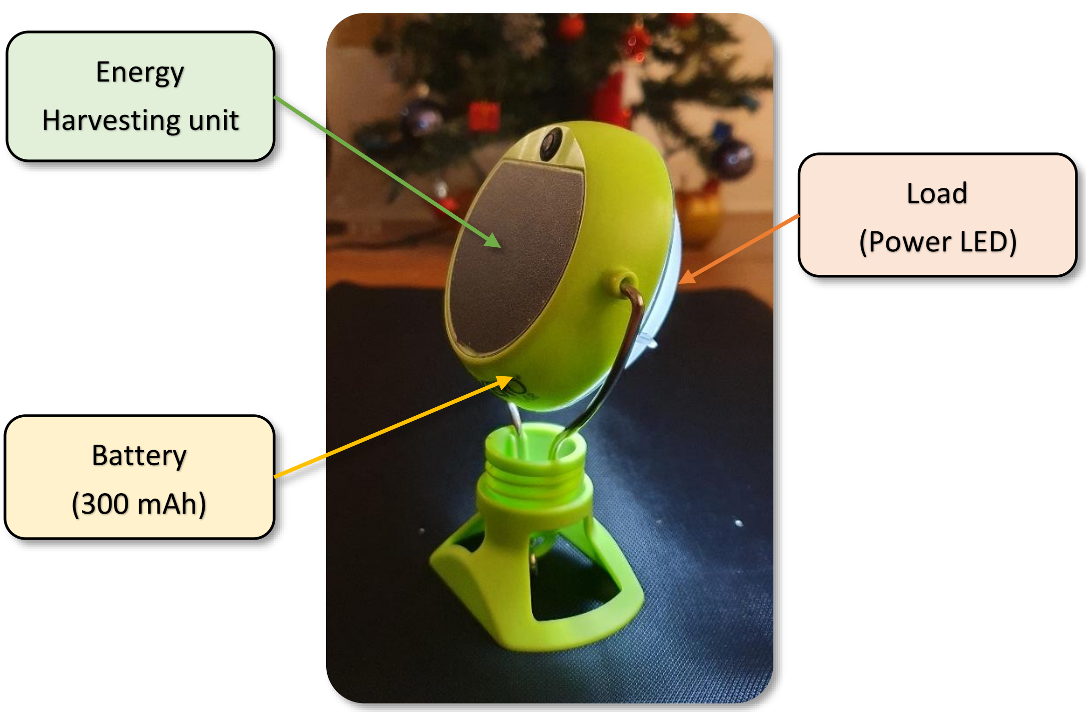
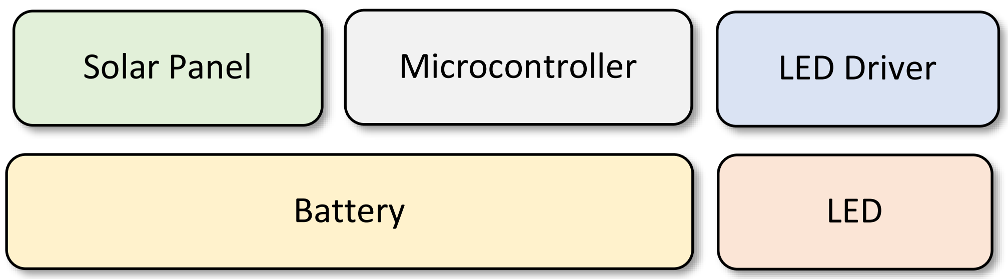


Figure 11: Sample Product for case study

Objective: Solar power lamp
Battery capacity = 500mAh
No of Solar cells = 7 (part number unknown)
LEDs: 1 power LED of typical current consumption of 50mA

Sample Project Block Diagram



Calculations:

$$Continuous\ current\ consumption\ by\ Power\ LED = 55\ mA$$

$$Theoretical\ battery\ backup = \frac{Battery\ capacity(mAh)}{Continuous\ current\ consumption}$$

$$= \frac{500}{55} = 9.09\ Hrs$$

Practically measured battery backup: 9 hours
If current consumption was 18mA, we would get battery backup of ~27 Hrs

Outcome of the experiment:

Our calculation for CUBIT falls between this range where battery backup for 480 mh battery with 18mA avg current consumption is around 24 Hrs. This verifies calculations against practical measurements.

- Finalized solar cell unit

Calculations:

As per calculations in spreadsheet bq25570SolarAppDesign.xlsx,
Minimum solar panel area required is $8mW/cm^2$

As per datasheet: solar cell (2994-KXOB25-12X1F-TB-ND), maximum peak power is 24.5mW per 1.54 cm^2

This implies power/cm^2 $= 24.5mW/1.54cm^2$

$$= 15.90mW/cm^2$$

Selected component satisfies this requirement of minimum $8mW/cm^2$

4.1.3 Version tracking using GitHub

Updated previous updates, libraries and calculation documents to github rajatchaple/ecen5833_s22_lpedt_project (github.com)

4.1.4 Timing information

Following are the critical timing parameters per module.

Table 7: Timing Information

Device	Parameter	Description	Min	Max
AS5147 (SPI)	tL	Time between CSn falling edge and CLK rising edge	350 ns	
	tH	Time between last falling edge of CLK and rising edge of CSn	50 ns	
	tMOSI	Data input valid to falling clock edge		
BNO055	fSCL	Clock frequency		400kHz
	fSUDAT	SDA Setup Time	0.1 us	
	HDDAT	SDA Hold TIme	0 us	
SHARP Memory LCD	fSCLK	Clock Frequency		1.1MHz
	tsSCS	SCS Setup time	6 us	
	thSCS	SCS hold time	2 us	
	tsSI	SI setup time	250 ns	
	thSI	SI hold time	350 ns	

4.1.5 Calculations for PMIC IC

- Studied reference design in bq25570 user guide in order to understand PMIC circuitry for our application.
- Also, used calculator provided by TI on BQ25570 data sheet, product information and support | TI.com to calculate Resistor values.

4.1.6 Battery specifications

Table 8: Battery specifications

Parameter	**Value**
Battery nominal Voltage	3.7V
Typical capacity	500mAh
Minimum capacity	480mAh
Charge voltage	4.2V
Standard current	0.2C-100 mA
Max charging current	0.5C – 250mA
Cut-off voltage	3V
Max discharging current	2C-1A
Power rating	1.78Wh

Battery Tolerances

Table 9: Battery Tolerances

Parameter	Value
Overcharge voltage	4.28 V ± 0.025 V
Overdischarge voltage	3.00 V ± 0.05 V
Over current range	1.0A to 4.0A
Charging operating temperature	+10°C to +45°C
Discharging operating temperature	-20°C to +25°C

4.1.7 High risk elements:

- Magnetic interference of two sensors
    - IMU has a magnetometer which is to be used for compass and the rotary encoder is also based on magnetic pulse. These two components can interfere with each other and show incorrect reading. As a measure to mitigate this risk, we will be placing the two components physically as far as possible from each other on the board.
- EMI interference
    - Similar to the issue mentioned, the magnetic field from these components can also generate electromagnetic interference which can disrupt the functionality of other components on the board especially inverted F-antenna for Bluetooth connection (radio frequency can be disrupted due to electromagnetic interference). The potential solutions to overcome EMI are filtering, shielding, or grounding.
- Dual charging system (USB and Solar cell)
    - As a power storage component, we are using a rechargeable LiPo battery. To recharge this battery, we are planning on using energy harvesting component - solar cells. Apart from the solar cells, we also intend to have a 5V USB charging port on the board.
    - The major drawback in this design is the unavailability of a power management IC to efficiently switch between solar cells and USB port. Even if we interface a USB port, we have to have a circuit design such that reverse current does not flow from battery to our energy harvesting device and also to automatically switch between solar energy and USB input.
    - In this circuit design, we plan to use Schottky diodes for fast switching and low voltage drop. In case we are unable to successfully implement this design, we will be eliminating use of USB charging port and use the solar power as our primary recharge source.

4.1.8 Project Schedule:

Table 10: Project Schedule

Task	Deadline
Altium Components Libraries	Feb 12, 2022
Altium Product Schematic	Feb 26, 2022
Altium Product Layout	March 5, 2022
Product Final Layout for Fabrication	March 12, 2022
Send PCCB board for fabrication	March 19, 2022

We are aligned with our project timelines except the task where our plan was to bring up LCD module last week. We will be achieving this task in upcoming week. Instead, this week we focused on our case study of sample project to verify our energy calculations.

4.2 Activities planned for the upcoming week:

- Finalizing Bulk capacitance
- Implement LCD driver
- Schematic of Power Management Unit